



# **System Qualities Ontology, Tradespace and Affordability (SQOTA) Project**

## **Phase 5**

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## EXECUTIVE SUMMARY

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### Motivation and Context

One of the key elements of the SERC's research strategy is transforming the practice of systems engineering and associated management practices- "SE and Management Transformation (SEMT)." The Grand Challenge goal for SEMT is to transform the DoD community's current systems engineering and management methods, processes, and tools (MPTs) and practices away from sequential, single stovepipe system, hardware-first, document-driven, point- solution, acquisition-oriented approaches; and toward concurrent, portfolio and enterprise- oriented, hardware-software-human engineered, model-driven, set-based, full life cycle approaches.

These will enable much more rapid, concurrent, flexible, scalable definition and analysis of the increasingly complex, dynamic, multi-stakeholder, cyber-physical-human DoD systems of the future. Four elements of the research strategy for SE Transformation are the following:

1. **Make Smart Trades Quickly:** Develop MPTs to enable stakeholders to be able to understand and visualize the tradespace and make smart decisions quickly that take into account how the many characteristics and functions of systems impact each other
2. **Rapidly Conceive of Systems:** Develop MPTs that allow multi-discipline stakeholders to quickly develop alternative system concepts and evaluate them for their effectiveness and practicality
3. **Balance Agility, Assurance, and Affordability:** Develop SE MPTs that work with high assurance in the face of high uncertainty and rapid change in mission, requirements, technology, and other factors to allow systems to be rapidly and cost-effectively acquired and responsive to both anticipated and unanticipated changes in the field
4. **Align with Engineered Resilient Systems (ERS):** Align research to leverage DoD's ERS strategic research initiative and contribute to it; e.g., ERS efforts to define new approaches to tradespace analysis.

"Systems" covers the full range of DoD systems of interest from components such as sensors and effectors to systems of systems that are full or parts of net-centric systems of systems and enterprises. "Effectiveness" covers the full range of needed System Qualities (SQs) such as reliability, availability, maintainability, safety, security, performance, usability, scalability, interoperability, speed, versatility, flexibility and adaptability along with composite attributes such as resilience, affordability, and suitability or mission effectiveness. "Cost" covers the full range of needed resources, including present and future dollars, calendar time, critical skills, and critical material resources.

The primary focus of RT-160, Phase 5 of the System Qualities Ontology, Tradespace and Affordability (SQOTA) project is on strategy 3, although its capabilities also support strategies 1, 2, and 4. It particularly focuses on the tradespace among a system's qualities, also called non-functional requirements or systemilities. The SQs differ from functional requirements in that they are systemwide properties that specify how well the system should perform, as compared to functions that specify what the system should perform. Adding a functional requirement to a system's specification tends to have an incremental, additive effect on the system's cost and schedule. Adding an SQ requirement to a system's specification tends to have a systemwide, multiplicative effect on the system's cost and schedule. Also, SQs are harder to specify and evaluate, as their values vary with variations in the system's environment and operational scenarios.

Further, the satisfaction of their specifications is much harder to verify than placing an X in a functional traceability matrix, as the verification traces to the entire set of system functions. It also requires considerable effort in analysis across a range of environments and operational scenarios. As a result, it is not surprising that problems in satisfying SQ requirements are the source of many DoD acquisition program cost and schedule overruns. Also, with some exceptions such as pure physical systems and pure software systems, there is little technology in the form of scalable methods, processes, and tools (MPTs) for evaluating the satisfaction of multiple-SQ requirements and their associated tradespaces for complex cyber-physical-human systems.

The increasingly critical DoD need for such capabilities has been identified in several recent studies and initiatives such as the AFRL "Technology Horizons" report (Dahm, 2010), the National Research Council's "Critical Code" Report (NRC, 2010), the SERC "Systems 2020" Report (SERC, 2010), the "Manual for the Operation of the Joint

Capabilities Integration and Development System" (JROC, 2012), and the DoD "Engineered Resilient Systems (ERS) Roadmap" (Holland, 2012). The particular need for Affordability has been emphasized in several USD(AT&L) and DepSecDef "Better Buying Power" memoranda BBP 1.0 and 2.0 (Carter et al., 2010-2013) and the recent BBP 3.0 White Paper (Kendall, 2014).

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## **SQOTA PHASE 5 CONTEXT: SUMMARY OF PHASES 1 THROUGH 4**

For SQOTA Phase 5 context, short summaries of SQOTA Phases 1 through 4 are provided next.

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### **PHASE 1 OBJECTIVES, APPROACH AND RESULTS**

The major objectives of the initial 5-month Phase 1 activity were to lay strong foundations for SQOTA Phase 2, including knowledge of Department of Defense (DoD) SQ priorities; foundations and frameworks for SQ tradespace analysis; extension and tailoring of existing SQOTA methods, processes, and tools (MPTs); and exploration of candidate Phase 2 pilot organizations for ITAP MPTs.

Four activities were pursued in achieving these objectives:

1. **SQ Definitions and Relationships.** Phase 1 included a discovery activity to identify and analyze DoD and other ility definitions and relationships, and to propose a draft set of DoD-oriented working definitions and relationships for the project.
2. **SQ Foundations and Frameworks.** This effort helped to build SQOTA foundations by elaborating key frameworks (process-based, architecture-based, means-ends based, value-based) anticipating further subsequent elaboration via community efforts.
3. **SQ-Oriented tool demos and extension plans.** This effort created initial demonstration capabilities from strong existing SERC SQ analysis toolsets and explored piloting by user organizations in the DoD Services.
4. **Program management and community building.** This effort included coordinating efforts with complementary initiatives in the DoD ERS, and counterpart working groups in the International Council for Systems Engineering (INCOSE), the Military Operations Research Society (MORS), and the National

Defense Industry Association (NDIA).

The Phase 1 results for activities 1 and 2 included initial top-level sets of views relevant to SQ tradespace and affordability analysis that provided an initial common framework for reasoning about SQs, similar in intent to the various views provided by SysML for product architectures and DoDAF for operational and architectural views. The views included definitions, stakeholder value-based and change-oriented views, views of ability synergies and conflicts resulting from ability achievement strategies, and a representation scheme and support system for view construction and analysis.

Phase 1 also determined that strong tradespace capabilities were being developed for the tradespace analysis of physical systems. However, based on sources such as the JCIDS survey of combat commanders' tradespace needs, it found that major gaps existed between commanders' SQ tradespace needs and available capabilities for current and future cyber- physical-human systems. The SERC also characterized the benefits and limitations of using existing tools to address SQ tradespace issues, via collaboration with other leading organizations in the DoD ERS tradespace area, such as the Army Engineer Research and Development Center (ERDC) and TARDEC organizations, NAVSEA, the USAF Space and Missile Systems Command; DoD FFRDCs such as Aerospace, Mitre, and the Software Engineering Institute; and Air Force and Navy participants via the SERC Service academies AFIT and NPS.

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## PHASE 2 OBJECTIVES, APPROACH AND RESULTS

As a result, the focus of Phase 2 was to strengthen the conceptual frameworks underlying SQ tradespace and affordability analysis, and to apply the methods and tools identified and extended in Phase 1 on problems relevant to *DoD*, using the information available from development of a large weapon systems and large automated information systems. The SERC worked with system developers directly and via participation and leadership in Government and industry working groups in such organizations as INCOSE, NDIA, and the Army-led Practical Systems and Software Measurement organization, to gain a deeper shared understanding of the strengths and limitations of the tradespace tools and methods developed under Phase 1 and elsewhere.

**Task 1: /TAP Foundations and Frameworks.** Phase 2 activities expanded the set of SQs represented in the tradespace, organized them into a more orthogonal value-based,



means- ends hierarchy, obtained initial results in identifying and quantifying the synergies and conflicts resulting from strategies to optimize individual SQs, and developed prototype tools for representing and applying the results.

**Task 2. iTAP Methods and Tools Piloting and Refinement.** The SQ-oriented tool demos performed in Phase 1 also led to Phase 2 interactions with DoD organizations, particularly TARDEC and NAVSEA, interested in their applicability in enhancing their systems engineering capabilities. These interactions led to refinements of existing methods and tools to address set- based vs. point design of ground vehicles and ships, and on extensions from physical systems to cyber-physical-human systems and to affordability analysis. Further interactions leading to piloting engagements included AFIT's use of the CEVLCC life cycle cost model and related T-X Training System Tradespace Analyses. The pilot program involved advanced pilot training aircraft, simulators and course instructional elements. Its pilot organizations were the Air Force life Cycle Management Center and the Air Education and Training Command. GTRI's

Framework for Assessing Cost and Technology (FACT) was extended beyond its initial support of USMC, and attracted several Army and Navy programs interested in piloting, extending, and tailoring its capabilities to other domains.

**Task 3. Next-Generation, Full-Coverage Cost Estimation Model Ensembles.** A third area of engagement starting from exploratory discussions in Phase 1 was a new task to develop Next- Generation, Full-Coverage Cost Estimation Model Ensembles, initially for the space domain, based on discussions and initial support from the USAF Space and Missile Systems Center (SMC). Phase 2 work on this topic involved several meetings with SMC and the Aerospace Corp. with USC and NPS to set context and initial priorities. These included addressal of future cost estimation challenges identified in the SERC RT-6 Software Cost Estimation Metrics Manual developed for the Air Force Cost Analysis Agency, and prioritization of research efforts based on strength of DoD needs and availability of DoD-relevant data. Exploratory activities were pursued with respect to a seeping of full-coverage of space system flight, ground, and launch systems; hardware, software and labor costs; and system definition, development, operations, and support costs, along with explorations of sources of data for calibrating the models.

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### PHASE 3 OBJECTIVES, APPROACH AND RESULTS

**Task 1: SQ Foundations and Frameworks.** MIT's Phase 2 research refined a SQs semantic basis for change-related SQs. and developed prototype tools for formal analysis of the results. Phase 3 extended the SQs semantic basis for change-related SQs, resulting from continuing literature review of SQs, collaborative work on formalization of the basis, and experience in applying the basis in historical cases. Progress and adjustments to the basis have been made as a result of feedback from other academic researchers, and specifically in MIT- UVA collaboration in their efforts on formalization and development of a REST (representational state transfer) web-based service implementation. This resulted in an expanded and more explicit representation for the semantic basis, as well as motivating the need to create a translation layer for practical use of the basis. Phase 3 also refined the SQ definitions, reviewed existing SQ definition standards, developed an initial SQs ontology reflecting the reality that the ilties have multiple definitions varying by domain, and multiple values varying by system state, processes, and relations with other ility levels. Phase 3 also expanded the initial 4x4 synergies and conflicts matrix into a full 7x7 inter-ility-class synergies and conflicts matrix, and 7 smaller intra-ility-class synergies and conflicts matrices.

**Task 2: SQ-Oriented tool demos and extension plans.** Phase 2 effort created initial demonstration capabilities from strong existing SQ analysis toolsets and explored piloting by user organizations, via collaboration with other leading organizations in the DoD ERS

tradespace area. Phase 3 broadened and deepened these initial contacts, including with such organizations as the Army Engineer Research and Development Center (ERDC) and TARDEC organizations, NAVSEA, the USAF Space and Missile Systems Command; DoD FFRDCs such as Aerospace, Mitre, and the Software Engineering Institute; and Air Force and Navy participants via the SERC Service academies AFIT and NPS. In particular, WSU and PSU advanced the SQOTA coordination with the ERS NAVSEA group, working with them to define the specific tradespace approaches and priorities for enhanced set-based design for ERS, that will complement and extend the tool and procedures they have been using. TARDEC was actively engaged as a partner for co-development, piloting and transition into use. The GTRI FACT-related capabilities were strongly co-funded and enhanced by and for the Army Engineer R&D Center (ERDC), other Army, Navy, and further USMC programs, including

strengthening and extension of the infrastructure for supporting and extending the initial FACT capabilities.

***Task 3: Next-Generation, Full-Coverage Cost Estimation Model Ensembles.*** Based on the exploratory needs and data assessments in Phase 2, a Phase 3 workshop including Air Force, Navy, aerospace industry, and SERC researchers concluded that there were strong needs for better estimation of operations and support costs, but that the data available lacked adequate cost driver information, except in the software area. The workshop recommended that the most promising initial areas to pursue would be for software development, systems engineering, and the use of systems engineering cost drivers to improve estimation of system development costs. Further research and workshops identified further sources of data and some shortfalls in current models in these areas, and developed requirements and draft frameworks for the next-generation models. These have been used in Phase 4 to develop and calibrate prototype models for systems and software engineering cost estimation models, and to pursue research in the use of the systems engineering model to better estimate system development costs.

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#### **PHASE 4 OBJECTIVES, APPROACH AND RESULTS**

##### **Task 1. SQ Foundations and Frameworks**

Rather than attempt a breadth-first elaboration of the 176 SQ Synergies and Conflicts strategies in the 7x7 matrix, including its ontology elements of Referents, States, Processes, and Relations for each strategy, the USC ontology-based research is a depth-first research effort on a particular SQ that touches all of the four major SQ categories. This SQ is Maintainability. It clearly drives Life Cycle Efficiency, as typically at least 75% of a system's Total Cost of

Ownership is spent on operations and maintenance. It is one of two means for achieving Changeability, involving external change vs. the internal change accomplished by Adaptability. It is clearly key to Dependability, as Maintainability in terms of Mean Time to Repair (MTIR) is the key relation between Reliability in terms of Mean Time Between Failures (MTBF) and

Availability in the relation  $\text{Availability} = \text{MTBF} / (\text{MTBF} + \text{MTIR})$ . And the key systems aspects being depended-upon are primarily the components of Mission Effectiveness.

This depth-first approach thus provided insights on the overall Product Quality ontology structure without having to consider all of the 176 strategies in depth. The insights resulted in changes to the SQ terminology, as shown in the main description of the Phase 4 Results. Examples are changing Resource Utilization to Life Cycle Efficiency, to be more compatible with the Better Buying Power terminology, and changing Flexibility to Changeability, to be better aligned with the MIT Quality In Use ontology structure.

The MIT Quality In Use ontology structure was refined to address further semantic aspects, and requirements for a translation layer to facilitate its use were developed, as elaborated in the main Phase 4 results section. Similarly, the U. Virginia Phase 4 research on formalizing both the MIT and USC ontologies is elaborated in the main Phase 4 results section. An initial semantic diagram relating the USC and MIT terms and relationships is also presented in the main Phase 4 results section.

#### **Task 2. SQ-Oriented tool demos and extension plans.**

The USC depth-first exploration of Maintainability identified the need for a better balance of attention during the system acquisition phase between optimizing on system acquisition cost-effectiveness and optimizing on system life-cycle cost-effectiveness, particularly for software, due to the major differences between software and software logistical aspects. This led to the development of a proposed framework of Maintainability Readiness Levels for Software - Intensive Systems. Again, details are provided in the main Phase 4 results section.

Other Task 2 Phase 4 Objectives, Tasks and Results summaries will be provided later.

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#### **TASK 3: NEXT-GENERATION, FULL-COVERAGE COST ESTIMATION MODEL ENSEMBLES**

The Task 3 Phase 4 Objectives, Tasks and Results summaries will be provided later.

#### References

(Carter et al., 2010-2013) Carter, A., et al., Better Buying Power Memoranda, <http://bbp.dau.mil/references.html>.

Dahm, 2010) Dahm, W., Technology Horizons, AF/ST-TR 10-01-PR, 15 May 2010.

(Holland, 2012) Holland, J. "ERS Overview," Proceedings, NDIA SE Conference, October 2012.

(JROC, 2011) Joint Requirements oversight Council, "Manual for the Operation of the Joint Capabilities Integration and Development System," Updated 31 January 2011.

(Kendall, 2014) Kendall, F., "Better Buying Power 3.0 White Paper," OUSD (AT&L), 19 September 2014.

(NRC, 2010) Scherlis, W. et al., Critical Code: Software Producibility for Defense NAS Press, 2011.

(SERC, 2010) B. Boehm, J. Bayuk, A. Desmukh, R. Graybill, J. Lane, A. Levin, A. Madni, M. McGrath, A. Pyster, S. Tarchalski, R. Turner, and J. Wade, Systems 2020 Strategic Initiative, Final Technical Report SERC-2010-TR-009, August 29, 2010.

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## PHASE 5 RESULTS SUMMARY

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### 1.2.1 TASK 1: SYSTEM QUALITIES (SQ) FOUNDATIONS: SQ ONTOLOGY

SQ Ontology (USC, AFIT, MIT, U.Virginia). A major development in 2016 was the publication of a workable ontology of the nature and relations of the SQs. It built upon partial ontologies by David Jacques and Erin Ryan at AFIT; by Adam Ross and Donna Rhodes at MIT; and Bany Boehm and Jo Ann Lane at USC, along with an initial formal definition of the relations among the SQs by Kevin Sullivan at U. Virginia. One part of the ontology, shown in Figure 1, organizes the SQs into a class hierarchy reflecting system stakeholders' value propositions (Mission Effectiveness, Life Cycle Efficiency, Dependability, Changeability), and the means for satisfying them. Other parts of the ontology identify the sources of variation in an SQ's numerical value with respect to stakeholder priorities; internal and external system states and processes; and synergy and conflict relations among the SQs.

**Table 1 Upper Levels of Stakeholder Value-Based SO Means-Ends Hierarchy**

Stakeholder Value-Based SO Ends	Contributing SQ Means
Mission Effectiveness	Stakeholders-satisfactory balance of Physical Capability, Cyber Capability, Human Usability, Speed, Endurability, Maneuverability, Accuracy, Impact, Scalability, Versatility, Interoperability, Domain-Specific Objectives

Life Cycle Efficiency	Development and Maintenance Cost, Duration, Key Personnel, Other Scarce Resources; Manufacturability, Sustainability
Dependability	Reliability, <u>Maintainability</u> , Availability, Survivability, Robustness, Graceful Degradation, Security, Safety
Changeability	Maintainability, Modifiability, Repairability, Adaptability
Composite SQs	
Affordability	Mission Effectiveness, Life Cycle Efficiency
Resilience	Dependability, Changeability

One Aspect of the ontology addressed in 2016 was to identify maintainability as a means of achieving several higher-level value propositions. It contributes to dependability as Mean Time to Repair (MTTR) in the relationship between Reliability as Mean Time Between Failures. This (MTBF) and Availability via the equation  $\text{Availability} = \text{MTBF} / (\text{MTBF} + \text{MTTR})$ . It also contributes to Changeability and Life Cycle Efficiency by making repairs and change requests less costly. Combined with the fact that DoD and most other organizations spend about 75% of their budgets on systems maintenance, this led us to do a deep dive on maintainability to determine the main sources of systems' maintenance costs and what could be done to reduce them.

This included data-analytics and experimental studies of alternative automated (Maintainability Index, Technical Debt) and human-assessed (Software Understanding) Maintainability metrics; and workshops with our industry and government affiliates to identify the major causes of Technical Debt and other maintenance difficulties. The results of the studies were that the human-assessed metrics were better predictors of maintenance effort, but that the automated methods were more efficient, and that the best approach was to use the automated methods to identify the parts of the software that would most benefit from human assessment. The results of the workshops were that the debt was technical, but its main root causes were non-technical.

A top-10 list of the main root causes follows: Separate organizations and budgets for systems and software acquisition and maintenance; Over concern with the Voice of the Customer; The Conspiracy of Optimism; Inadequate system engineering resources; Hasty contracting that focuses on fixed operational requirements; CAIV-limited system requirements; Brittle, point-solution architectures; The maintainers' Vicious Circle; Stovepipe systems; and Over-extreme forms of agile development.

As a way of focusing management attention on the life cycle operational needs and financial benefits of developing maintainable systems, the project has developed a counterpart to the Technology Readiness Level framework, called the System/Software Maintainability Readiness

Framework (SMRF), shown in Table 2. Several DoD-community organizations are evaluating it for use

**Table 2 Software-Intensive Systems Maintainability Readiness Framework**

<b>Software-Intensive Systems Maintainability Readiness Framework (SMRF)</b>			
<b>SMR Level</b>	<b>OpCon, Contracting: Missions, Scenarios, Resources, Incentives</b>	<b>Personnel Capabilities and Participation</b>	<b>Enabling Methods, Processes, and Tools (MPTs)</b>
<b>9</b>	5 years of successful maintenance operations, including outcome-based incentives, adaptation to new technologies, missions, and stakeholders	In addition, creating incentives for continuing effective maintainability. performance on long-duration projects	Evidence of improvements in innovative O&M MPTs based on ongoing O&M experience
<b>8</b>	One year of successful maintenance operations, including outcome-based incentives, refinements of OpCon. Initial insights from maintenance data collection and analysis (DC&A)	Stimulating and applying People CMM Level 5 maintainability practices in continuous improvement and innovation in, e.g., smart systems, use of multicore processors, and 3-D printing	Evidence of MPT improvements based on maintenance DC&A-based ongoing refinement, and extensions of ongoing evaluation, initial O&M MPTs.
<b>7</b>	System passes Maintainability Readiness Review with evidence of viable OpCon, Contracting, Logistics, Resources, Incentives, personnel capabilities, enabling MPTs, outcome-based incentives	Achieving advanced People CMM Level 4 maintainability capabilities such as empowered work groups, mentoring, quantitative performance management and competency-based assets	Advanced, integrated, tested, and exercised full-LC MBS&SE MPTs and Maintainability-other-SQ tradespace analysis

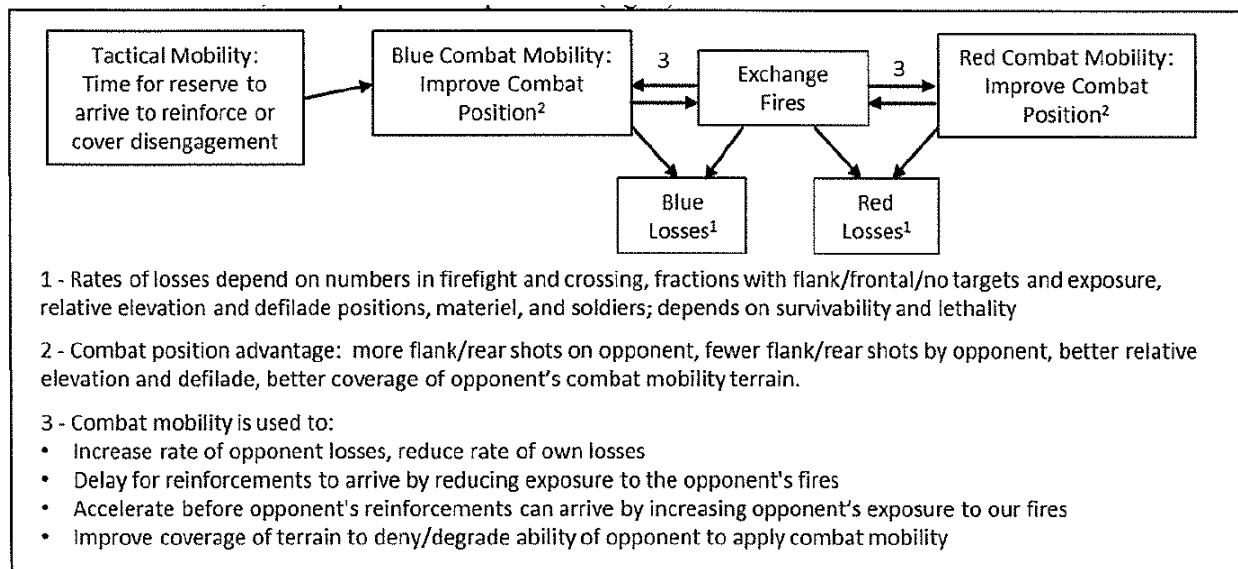


6	Mostly-elaborated maintainability OpCon, with roles, responsibilities, workflows, logistics management plans with budgets, schedules, resources, staffing, infrastructure and enabling MPT choices, V&V and review procedures.	Achieving basic People CMM levels 2 and 3 maintainability practices such as maintainability work environment, competency and career development, and performance management especially in such key areas such as V&V, identification & reduction of technical debt.	Advanced, integrated, tested full-LC Model-Based Software & Systems (MBS&SE) MPTs and Maintainability-other-SQ tradespace analysis tools identified for use, and being individually used and integrated.
5	Convergence, involvement of main maintainability success-critical stakeholders. Some maintainability use cases defined. Rough maintainability OpCon, other SCSHs, staffing, resource estimates. Preparation for NDI and outsource selections.	In addition, independent maintainability experts participate in project evidence-based decision reviews, identify potential maintainability conflicts with other SQs	Advanced full-lifecycle (full-LC) O&M MPTs and SW/SE MPTs identified for use. Basic MPTs for tradespace analysis among maintainability & other SQs, including TCO being used.
4	Artifacts focused on missions. Primary maintenance options determined, Early involvement of maintainability SCSHs in elaborating and evaluating maintenance options.	Critical mass of maintainability SysEs with mission SysE capability, coverage of full M-SysE skills areas, representation of maintainability success-critical-stakeholder organizations.	Advanced O&M MPT capabilities identified for use: Model-Based SW/SE, TCO analysis support. Basic O&M MPT capabilities for modification, repair and V&V: some initial use.
3	Elaboration of mission Operational Concept (OpCon), Architectural views, lifecycle cost estimation. Key mission, O&M, success-critical stakeholders (SCSHs) identified, some maintainability options explored.	O&M success-critical stakeholders provide critical mass of maintainability-capable SysEs Identification of additional. M-critical success-critical stakeholders.	Basic O&M MPT capabilities identified for use, particularly for OpCon, Arch, and Total cost of ownership (TCO) analysis: some initial use.
2	Mission evolution directions and maintainability implications explored. Some mission use cases defined, some O&M options explored.	Highly maintainability-capable Systems Engineers (SysEs) included in Early SysE team.	Initial exploration of O&M MPT options
1	Focus on mission opportunities, needs. Maintainability not yet considered.	Awareness of needs for early expertise for maintainability. concurrent engr'g, O&M integration, Life Cycle cost estimation	Focus on O&M MPT options considered

## 1.2.2 TASK 2: METHODS AND TOOLS PILOTING AND REFINEMENT

Other universities on the SQOTA team are focusing on MMPTs for strengthening the SQ aspects of systems engineering in the context of the ontology and recent DoD emphasis areas such as Model-Based Systems Engineering (MBSE), Modular Open Systems Architecture (MOSA), and Set-Based Design (SBD). Below is a summary of the work being done by Gaty Witus at Wayne State University with TARDEC; similar work is being done by Michael Yukish at Palm State University on Naval applications

**Wayne State U. MMPTs.** We are working with the US Army TARDEC to develop tradespace models supporting key ground vehicle system acquisition decisions. We are leveraging related work in a separate project for DARPA on the "Ground Vehicle Experimental Technologies" (GVX-T) program (fig. 1). The expressed need was for tradespace models and tools to make armor protection versus mobility tradeoffs decisions. Different factors enter at different tradespace perspectives (fig. 2). The chain links affordability to the design, capability, and mission tradespaces. We began developing a quantitative tradespace model for ground vehicles by first developing a qualitative model of the dependencies among design decisions, resulting vehicle characteristics, and operational capabilities (fig. 3).



**Figure 1 Model of combat effectiveness at the “tip of the spear” – interaction of combat mobility, lethality, and survivability plus the impact of tactical mobility and availability of reserve on combat decision and outcomes**

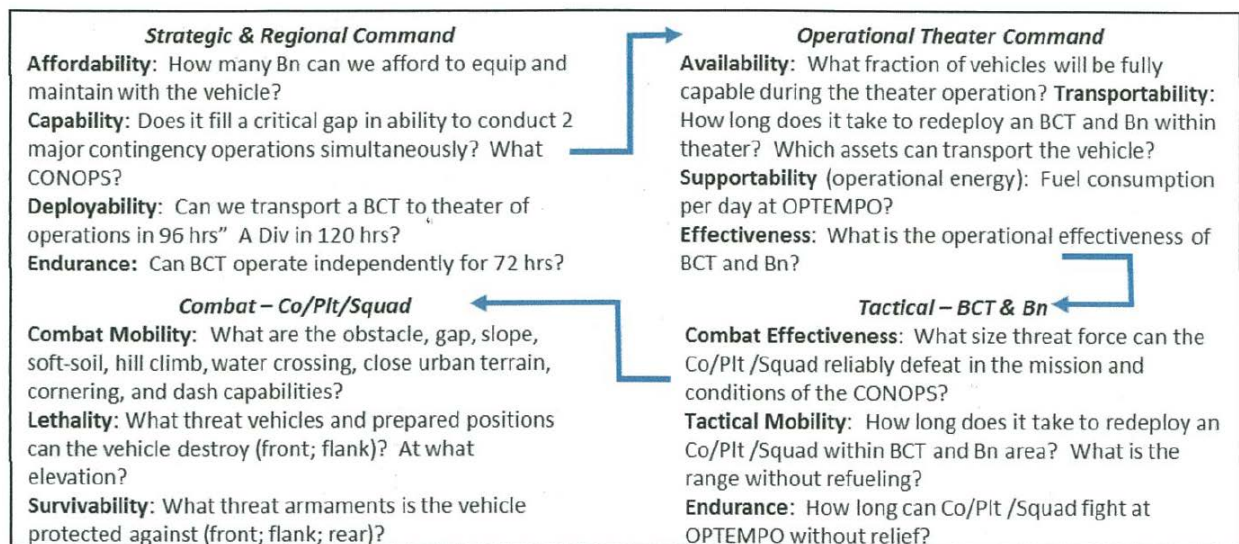


Figure 2 Affordability-capability-design tradespace model from command perspectives

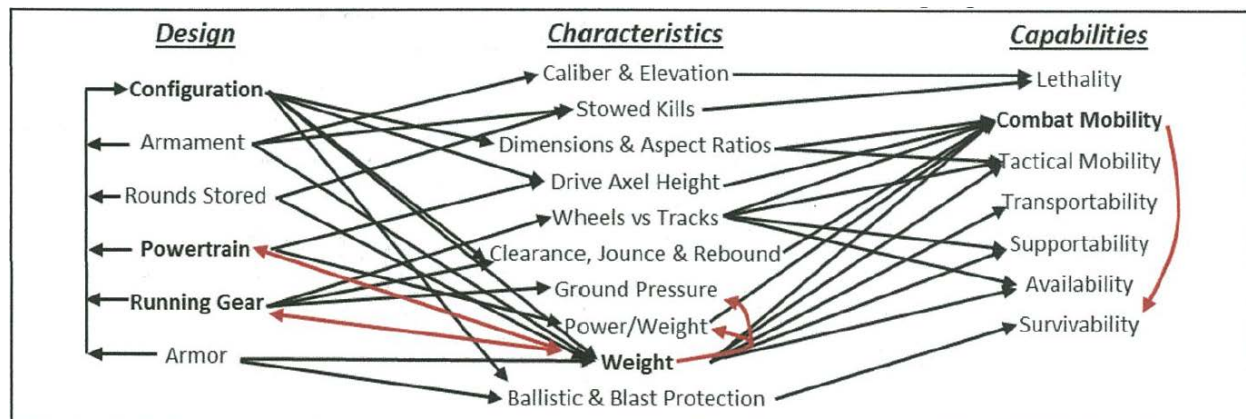


Figure 3 Dependency tradespace model

**AFIT and NPS MMPTs.** Another SQOTA collaborative effort in the MBSE area is being pursued by David Jacques at AFIT and Ray Madachy and Kristen Giammarco at NPS, in the area of coordinated drones performing intelligence-surveillance-reconnaissance (ISR) functions. Figure 4 provides an example of their modeling.

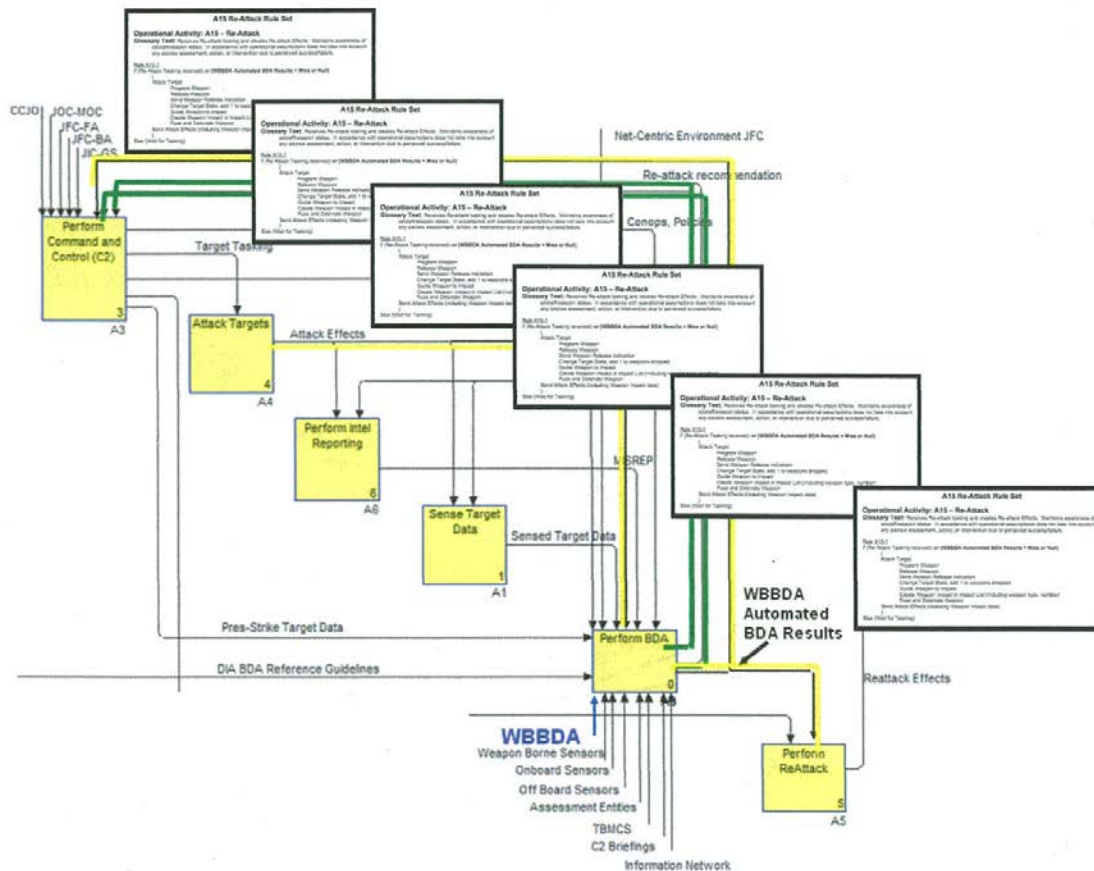


Figure 4 Example AFIT-NPS Coordinated-Drone Operational Model

**GTRI MMPTs.** The Georgia Tech Research Institute (GTRI) has also successfully transitioned its SQOTA (previously called ITAP, for ilities Tradespace and Affordability Project) research to several DoD organizations, led by Tommer Ender, Valerie Sitterle, and Daniel Browne at GTRI. Here are two examples.

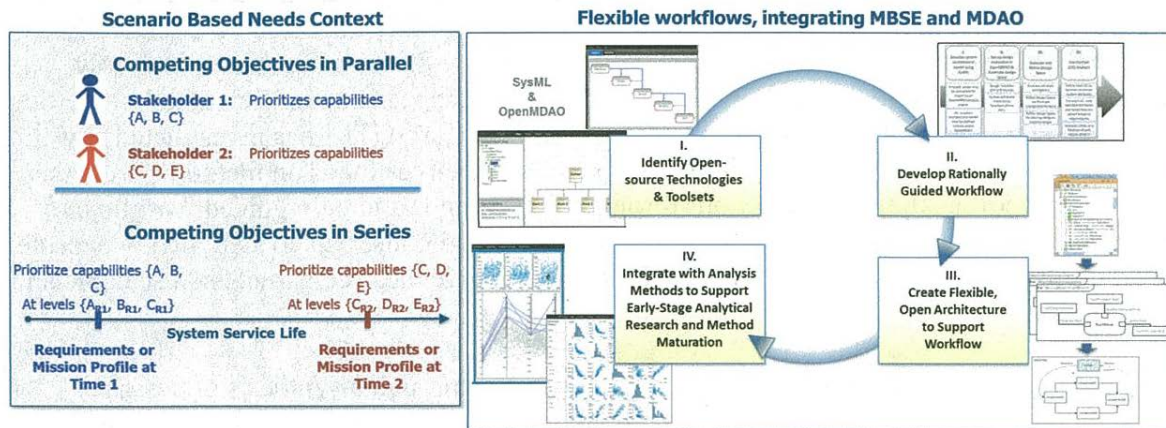
The SQOTA effort seeks to better analyze the tradespace of ilities (e.g., affordability, flexibility, reliability, usability, and interoperability) that are vitally important to effective Pre-Milestone a tradespace exploration and analysis for the DoD. Ilities, now more commonly referred to as system qualities (SQs), are frequently under-emphasized non-functional properties or quality attributes of systems. In support of the SQOTA effort, GTRI has investigated new methods and constructs for design exploration. GTRI's objectives focus on methods, processes, and tools to support analytical formations through flexible and rationally guided workflows. There are two primary thrusts to the research: 1) methods and constructs to analytically execute formalisms, and 2) processes and tools that help operationalize these constructs in a scalable and traceable manner.

GTRI's guiding vision is to discover a "best" set of options through a synthesis of design definition, tradespace generation, and decision analysis. The work began by leveraging previous GTRI research for authoring system engineering models in an SysML-like fashion through a web browser and using those models to execute design tradespace exploration. For SQOTA, GTRI began to extend these capabilities to allow feedbacks within the design process and compatibility with NASA's OpenMDAO framework. OpenMDAO is an open-source Multidisciplinary Design Analysis and Optimization (MDAO) framework developed by NASA Glenn and Langley Research Centers for use as an integrated analysis and design environment. By incorporating OpenMDAO alongside other open source technologies, GTRI laid the groundwork for linking multiple disparate models or other analysis tools in a single design structure matrix. As this work matured, GTRI focused on the data pipelining aspects of how to combine various analytical and decision making tools into a comprehensive but flexible framework. By allowing decision makers to preemptively sketch and organize flexible workflows incorporating these elements as building blocks, we enable a more effective synthesis of design definition, tradespace generation, and decision analysis.

Alongside these efforts, GTRI collaborated with ITAP team members at the University of Southern California and Naval Postgraduate School to interface existing cost models with SysML-based systems models. Unifying these areas of work provides the basis for next-generation cost modeling approaches that offer estimates of the system engineering effort costs, measure the complexity of the effort, and show how those aspects relate to one another. This work is being extended to system of systems problems with building blocks in SysML that leverage the COSYSMO-SoS/COCOMO legacy, and being validated against healthcare SoS case studies.

Throughout the development process and method inclusion, this effort and its future maturation seeks to preserve an open framework and approach that promotes quantitative and qualitative transparency of the tradespace refinement. Our goals are to ensure that the workflow and toolset support easy inclusion of analytical constructs that may be developed on other ITAP efforts to evaluate differentilities in different ways. Our work towards unifying the design, decision variable, and objective spaces in a flexible framework is being leveraged and matured under the DoD's Engineering Resilient Systems program to support effective and efficient design and development of complex engineered systems across their lifecycle.





**Figure 5 Transitioning ITAP – Successfully transitioned methods and approaches developed under ITAP to other DoD programs**

**Engineered Resilient Systems (ERS)** is one of seventeen DoD Communities of Interest led by the US Army Corps of Engineers. One of its primary goals is to develop an integrated, trusted, computational environment supporting all phases of the DoD's acquisition and operational analysis. This will result in a series of government owned and hosted tools to support. One of these tools, the "ERS TradeBuilder" is built by GTRI to conduct executable, model based systems engineering and support trade studies.

The "Define" segment of the ERS TradeBuilder enables a user to use Model Based Systems Engineering best practices. Users can define the Problem, to include decomposing system requirements from operational needs. Users can further define the System of interest, to include a physical decomposition according the MIL-STD-881C Work Breakdown Structure. Finally, users can define the Analysis technique which will be used (to include Modeling and Simulation).

Next, the "Execution" portion of the toolset enables a user to run a tradespace using high fidelity Modeling and Simulation leveraging the DoD's High Performance Computing (HPC) assets. Users can define ranges for the attributes of interest and select the appropriate HPC asset to leverage.

The final component of the ERS TradeBuilder is "Explore", where a user can conduct a wide variety of analysis to include Analysis of Alternatives, requirements feasibility, and other trade studies. The Explore portion of ERS TradeBuilder enables a user to customize a dashboard with a number of analytical tools. ERS TradeBuilder's Exploration capability enables a user to customize a dashboard with relevant analytical tools such as interactive scatter plots, histograms, and stop-light scoring charts. The user can further score the candidate systems according to overall Value using utility functions.



Figure 6 Engineered Resilient Systems “TradeBuilder”

### 1.2.3 TASK 3: NEXT-GENERATION, FULL-COVERAGE COST MODELS (USC, NPS)

Trends affecting system and software engineering practices such as internets of things, 3D printing, cloud services, big-data analytics, autonomic and learning systems, agile methods, and asymmetric threats, such as for cyber security, present challenges for DoD systems and software engineering practices, and also for estimating their costs and their impact on Affordability. The SQOTA Next-Generation Cost Models effort, with Co-PIs Barry Boehm and JoAnn Lane at USC and Ray Madachy at NPS, has made significant progress in defining next-generation versions of the COCOMO II software cost model (COCOMO III, led by Brad Clark at USC), and the COSYSMO 2.0 systems engineering cost model (COSYSMO 3.0, led

by Jim Alstad at USC). For COCOMO III, we have concluded that there will be no single model that is good for estimating all of the challenge areas above, and are prioritizing to create an initial version that best fits most of DoD's major project types.

For COSYSMO 3.0, in 2016 we achieved a major milestone in completing an Expert-Based Model. Our workshops and weekly expert telecons with industry, government, and academia representatives resulted in gathering complete set of expert judgments about the form and parameters of the model, so that we now have a fully developed interim model. The remaining step is to gather actual project data and combine that with the expert opinions to yield the final model. The 2016 events at which we had half-day working group sessions for COSYSMO 3.0 and often COCOMO III were the Army- and Navy-sponsored Practical Systems Measurement User Group (February), the Ground Systems Architecture Workshop (March), USC CSSE's Annual Research Review (March), the Navy and NGA-sponsored SoftWare and IT Cost Analysis Solutions Team meeting (August), and USC CSSE's COCOMO Forum (October).

The net result is shown in Figure 7, which shows the expert-consensus-determined values of the COSYSMO 3.0 effort multiplier ratios (EMRs) of the revised cost drivers: the ratio of their maximum value to their minimum value. Generally, cost drivers with larger EMRs are more important to a cost estimate than cost drivers with smaller EMRs. DFR is Development for Reuse.

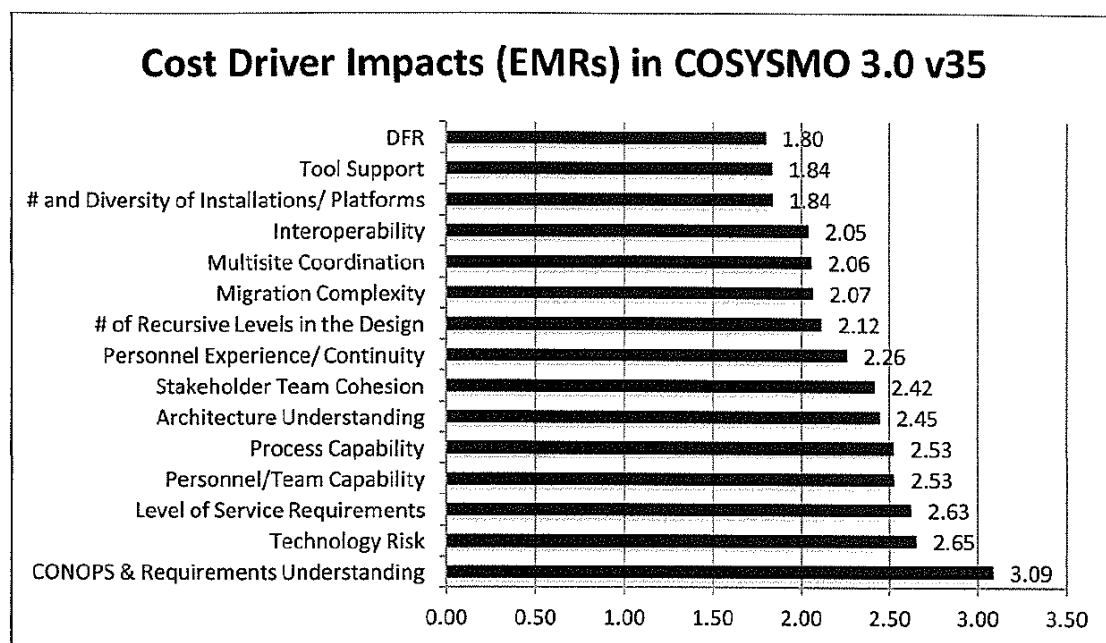


Figure 7 Expert-Based COSYSMO 3.0 Effort Multiplier Ratios



Phase 6 will continue the three primary tasks (Tasks 1- 3). Overall summaries of the tasks are provided next, followed by summarized Phase 6 deliverables.

### **Task 1. Research and Develop SQ Scientific Foundations**

This task will continue to expand, coordinate, and evolve two complementary ontologies for the SQs: a Product Quality, means-ends framework being evolved at USC, and a Quality-in-Use semantic framework for change-oriented SQs being evolved at MIT, with formal definitions for each being evolved at U. Virginia. Each will have compatible definitions of the key DoD SQs, and associated methods and tools for making formalizations accessible to the systems engineering research and practitioner communities for validation against the needs of practice. The Product Quality framework will continue to populate its synergy and conflict relationships among the SQs; to expand the quantification of the synergies and conflicts; and to refine the prototype tools for representing and applying the results. It will also develop complementary views for addressing DOD high-priority SQ-related issues dealing with uncertainties such as sources of change, early cost-effectiveness analysis, and Total Cost of Ownership analysis. It will also develop and apply scientific theories to validate the capabilities and consistency of the frameworks, models, methods, processes, and tools researched and developed.

*Research team: Primarily USC (lead), MIT, UVA*

### **Task 2. SQ Methods, Processes, and Tools (MPTs) Piloting and Refinement**

This task will follow up on the engagements with DoD organizations pursued in Phases 2 through 4, to continue to pilot the application of SERC methods and tools to DoD-system SQ tradespace and affordability issues, particularly in the cyber-physical-human systems and economic analysis areas. The methods and tools will continue to be refined, based on the results of the pilot applications. Representative activities will include efforts to:

- Experiment with tailoring existing or new SQ tradespace and affordability MPTs for use by early adopter organizations
- Train early adopters in their use, monitor their pilot usage, and determine areas of strengths and needed improvements, especially in the MPTs' ilities
- Extend the MPTs to address the top-priority needed improvements
- Work with early adopters to help transition the improved MPTs into their use
- Identify and pursue further improvements for the early adopters or for more general usage

The Primary Research Team will be as follows: Wayne State U. {lead}, AFIT, GT, NPS, PSU, and USC. MIT and UVA will selectively participate based on their Foundations MPTs.

- Army TARDEC, Navy NAVSEA, NAVAIR, SPAWAR: WSU, GT, NPS, PSU, USC
- USMC: GaTech, others
- USAF: AFIT-ASC; USC-SMC

### **Task 3. Next-Generation, Full-Coverage Cost Estimation Model Ensembles.**

Beginning with work in the space domain with USAF/SMC and the Aerospace Corp., this task has refocused on the two areas for which the needs and availability of data are the strongest: overall-DoD next-generation versions of the COCOMO model for software cost and schedule estimation and the COSYSMO cost model for systems engineering cost and early-phase schedule estimation.

*Research team: Primarily USC (Lead), NPS, AFIT*

### **Task Statements for Phase 6**

#### **Task 1. System Quality (SQ) Foundations**

**MIT.** Continue work with Mitre on extension and application of Changeability semantic basis. Extend semantic basis to selected Mission Effectiveness qualities. Develop capabilities for using semantic basis in Epoch-Era analysis.

**USC.** Extend Maintainability data analytics, using cloud services to track patterns of increase and decrease of Mean Time to Repair and Technical Debt. Continue experimental comparison of automated and human Maintainability assessment approaches, and develop guidelines for their complementary use.

Pilot, evaluate, and refine SYStem/Software Maintainability Readiness Framework (SMRF) on representative projects.

Explore similar elaboration of data analytics and Synergy & Conflict analysis for Dependability attributes: Reliability, Availability, Safety, Security, Robustness, Graceful Degradation. Use results to participate in update of SEBoK Specialty Engineering update.

Explore variant definitions of Resilience as combinations of Dependability and Changeability variants.

**USC-UVa.** Continue elaboration, exploratory application, evaluation, and refinement of formal System Quality definitions.

#### **Task 2. System Quality {SQ} Methods, Processes, and Tools (MPTs) Piloting and Refinement**

**AFIT, NPS.** Continue to elaborate DoDAF representation of partially-executable Operational and Systems Architecture, using associated Model-Based Systems Engineering (MBSE) tools such as SysML. Monterey Phoenix (MP), Cooperative unmanned Surveillance System (CUSS), COSYSMO, and further capabilities such as set-based modeling and Orthogonal Defect Classification COQUALMO for automated analysis of off-nominal UAV ISR operational scenarios, such as jamming, evasion, and camouflage. Apply, evaluate, refine, and extend system and models based on experimentation using nominal and off-nominal UAV ISR operational scenarios at Air Force drone-based mission testbed.

Examples of extensions from early Phase 5 studies include going from a basic multi-vehicle architecture using Small UAS to locate, confirm, track and engage widely dispersed targets. Basic architectural variations included numbers of vehicles, quality (performance measures) of the sensors, and C2 variations that considered operator-in-the-loop versus full autonomous operation. For Phase 6, we are developing a more complex architecture based on Small UAS providing remote targeting support for larger, standoff vehicles. Architectural views included requirements diagrams, functional decomposition (hierarchical), activity diagrams, block definition diagrams, and interface definition both across system elements and at the subsystem level within a system element. This level of definition will include operational threads, requirements, and interfaces at the appropriate decomposition level as direct input to parametric cost models. The thorough and detailed SysML model comprising size inputs will enable a COSYSMO cost estimate and extrapolated full lifecycle cost, amenable to later architectural variations.

**GTRI.** For Phase 6, GTRI will extend and mature the proof-of-concept PAW framework and associated tools developed in Phase 5. Specifically, we will investigate different approaches to capturing and characterizing dimensions of operational context relevant to DoD materiel design and development. This includes methods and processes through which the PAW framework may help us more efficiently and effectively (a) generate contextual tradespace data driven by both the physics of the problem as well as the operational needs, and (b) address contextual and other non-simple sources of uncertainty in tradespace analysis. Together, these thrusts will help the DoD community address more complex environments, operational scenarios, and multi-criteria analyses within an executable toolset. To accomplish these goals, GTRI will focus on leveraging the flexibility and customizable modularity of the PAW framework to investigate these methods and processes by comparing and contrasting SE approaches across problem scales. We will compare these methods and processes to the traditional, linear tradespace generation and multi-criteria decision analysis techniques. The goal is to address how we can intelligently create the data we need to answer SE questions critical to understanding what is driving decisions for DoD decision makers. These efforts will be piloted using a Jupyter notebook platform to promote collaborative use and pathways to interoperability for the SERC SQOTA team members and DoD sponsors. We will demonstrate application of these capabilities to sample problems illustrative of the DoD challenges.

**WSU.** WSU will work with TARDEC to develop a tradespace analysis model for ground vehicle development in the context of the Third Offset Strategy and the US Army Combat Vehicle Modernization Strategy.

### **WSU Task 1: Tradespace Framework for Collaborative Concept Development and Design**

This task will be conducted in collaboration with US Army, TARDEC, working with PhD candidates with SMART scholarships from TARDEC.

Task 1a. We will expand the stakeholder-perspective tradespace model previously developed to include the other factors and relationships described in the Army Combat Vehicle Modernization Strategy.

Task 1b. We will refine the statements of the stakeholder perspectives to address impact on and contribution to combined arms operations considerations since no vehicle is designed to or operates in isolation, but as part of a combined arms "System of Systems."

Task 1c. We will convert the dependency diagram format to relational statements in executable code to trace logical dependencies, and to evaluate quantitative dependencies (when quantitative dependency relationships are feasible and available).

Task 1d. We will complete expanding the model with a set-based design value function in order to address adaptability of modular systems, and the value of the ability to reconfigure and repurpose a vehicle platform as need to address potential future adversary conditions and adaptations. This work will complete the progress towards formulating a set-based value function that treats the vehicle as developed and procured as defining a set of potential future configurations, mission module and kit upgrades, to deal with uncertain and adaptive adversaries over the useful life of the system. A graduate student is completing his PhD dissertation on this topic, and will defend in 2017.

The set value function and the stakeholder-perspective model are the key elements to envisioning collaborative "set-based" design in ground vehicle conceptualization and specification.

### **WSU Task 2: Quantitative Tradeoff Models**

This task will be restricted in scope to mobility-survivability-lethality tradespace from the tactical and combat perspectives. The task will build on and extend the mobility-survivability tradespace state-transition computational modeling conducted for DARPA as part of the GVS-T project. It will extend the computational model to include lethality, as shown in Figure 3.

This is the minimal viewpoint from which to address tradeoffs between combat mobility and tactical mobility. This has been an historic gap. Existing methods, tools and procedures to develop mobility performance specifications (P-Specs) have not addressed the interaction effects and dependencies. The combat perspective is needed to justify combat mobility characteristics, while the tactical perspective of reinforcement and exploitation is needed to justify tactical mobility. The extension to quantifying the tradespace adds (a) lethality and (b) reinforcement to the quantitative model developed for the DARPA/TARDEC GVX-T project.

The two different mobility activities are needed to address wheel-vs-track issues. Armor protection and combat mobility have a complex interaction. Armor adds weight which decreases mobility which increases the time exposed to threats and the time to circumvent threat obstacles. Mobility enables evasive maneuver which improves survivability even when the threat weapon overmatches the US armor.

Armor is effective only when it overmatches the threat weapon- which leads to step functions in the value of armor. The distribution of armor is also part of the tradespace (frontal arc vs 360 protection) - mixed solutions are possible. Combat mobility impacts the time US vehicles have frontal vs side exposure. Lethality, enabled by combat mobility, is also part of the equation. Historical efforts to develop a "light tank"- e.g., the Sheridan, light enough for air transport with lethal capability, but lightly armored- proved ineffective and/or inefficient. The MPF is at risk of the same fate. The land combat community has not resolved tradeoffs between operational and tactical mobility vs combat mobility in the context of the armor and armament tradeoffs, and threats & operating conditions.

The Third Offset vision of operating challenges includes operations in dense urban environments and megacities in which only smaller, lighter vehicles can operate without air superiority or air support. We cannot solve this tradespace decision challenge in the next 12 months under limited budget. Deployability and in-theater transportability are overriding concerns from the strategic perspective, as are (a) the time and cost to Initial Operational Capability, and (b) the time and cost to transition the force. These are complex issues, beyond the budget of this task.

Within the budget of this task, we propose to deliver a quantitative tradespace model for propulsion, armor and armament in the context of combat and tactical operations. This will be demonstrated in the context of armor and mobility tradeoffs.

### **WSU Task 3: Autonomy and Manned-Unmanned Teaming to Enlarge the Tradespace**

Enlarging the tradespace happens when technologies enable possibilities that were previously infeasible. Given the resource constraints we can only begin to scratch the surface of the tradeoffs that autonomy and manned-unmanned teaming enables.

In this task we will use the models and frameworks produced from tasks 1& 2 as the model to explore the impact of removing or reducing the crew on cost and operational effectiveness. Within this limited scope, we will continue to focus on mobility, lethality and survivability at the system design level, and at higher levels of strategic, operational and tactical mobility.

The critical tradespace questions are (a) what "autonomous" and "manned-unmanned teaming" are needed for what operations?, and (b) how does "autonomous" and "manned- unmanned teaming" expand the design space and change the tradespace?

These questions are critical for the ground vehicle development community to respond to the Third Offset Strategy to employ autonomy technologies to achieve decisive advantage.

**PSU.** Continue to exercise, evaluate, refine, and extend set-based design (SBD)-enhanced tools for ground-based, sea-based, and air-based vehicles and their mission performance, in concert with NAVSEA and NAVAIR, including extensions for a tradespace decision structure that identifies key tradeoff analyses and the system development decisions that they support.

All. Identification and initial implementation of interoperability facilitation capabilities among SQ MPTs.

### **Task 3. Next-Generation Cost Estimation Models**

**USC, NPS.**

#### COSYSMO 3.0. Next-Generation Constructive Systems Engineering Cost Model.

Phase 5 completed the definition of COSYSMO 3.0, including experience-based refinement of the basic model and extensions for the effects of system reusability, reuse, requirements volatility, and systems of systems integration, and developing an initial quantitative model based on expert- consensus definitions of the quantitative sizing, cost driver, and scale factor parameters. Phase 6 will evaluate basic usage of the initial model, and gather data on completed projects for calibration to project data and Bayesian integration of the expert-based and data-based model parameters. Activities will include experience-based refinement workshops at the 18th Army-Navy-CARD Practical Systems Measurement Users Group (PSMUG) Workshop in June 2017, the 32<sup>nd</sup> USC COCOMO/System and Software Cost modeling (COCOMO/S&SCM) Forum in October 2017, and the 21<sup>st</sup> Aerospace Corp.-USAF Ground Systems Architecture Workshop (GSAW) in February-March 2018.

COCOMO III. Next-Generation Constructive Software Cost Model. Phase 5 determined that a single software cost model would not be able to cover the wide variations among software development for major systems, domain cloud-services applications, mobile web-based applications, and various forms of agile, Kanban, SAFE, and DevOps projects. For Phase 6, the focus will be on a version of COCOMO III for major systems, including expert-based parameter definitions, an initial expert-based quantitative model, and similar workshops at the PSMUG, COCOMO/S&SCM, and GSAW events.

USC, NPS, GTRI. GTRI and collaborators USC and NPS outlined a SysML cost modeling roadmap in the 2015-2016 report. For Phase 6, the proposed next steps for 2017-2018 along that roadmap include maturing this work along the lines of capability extensions using new tools, infusing context into those capabilities, and demonstrating the capabilities in case studies relevant to the DoD. For the extension work, GTRI proposes to create the next round of front-ends based on OpenMBEE and add new functionality to the SysML cost modeling building block library. Specifically, the work will focus on creating new building blocks to support (a) software cost modeling (via the COCOMO technique), (b) hardware cost modeling (via the Advanced Missions Cost Model (AMCM) technique), and (c) adding COSYSMO 2.0/3.0 aspects including considerations for reuse, risk, etc. The capabilities will focus on addressing the broader affordability tradespace context and the feasibility of auto-generating inputs to COSYSMO etc. from a regular SysML-based system model. GTRI will work with USC and NPS to demonstrate application of these capabilities to case studies relevant to the sponsor and investigate having the growing community of OpenMBEE users as beta testers of the SysML cost modeling building blocks.

- **Design and Demonstrate ISR UAV Tradespace.** The power of new tools such as MagicDraw and ModeiCenter is the integration with analysis tools, across a network or on the same machine. SysML has traditionally only captured and documented the operational concept, system requirements, activities/tasks, organizations and information flows, including possible physical instantiations. New MBSE tools facilitate analysis such as optimization, simulation, design of experiments, assessment, sensitivity analysis and statistical hypothesis testing and regression. For this project, such trades and characterizations could examine collaborative and vehicle swarming algorithms, increasing autonomy on multi-vehicle, and single operator operations. Likewise, the effects on environmental variables within the architecture, such as communications and/or GPS jamming, air defenses, evasion, camouflage, and other factors could define the scenarios. These types of trades demonstrate how a business case for varying technologies, capabilities or designs could be accomplished, if cost information is included.
- **Develop life cycle cost model interfaces for the various components of the architecture, and embed them within a larger stochastic life cost estimating approach to evaluate cost effectiveness in an uncertain future environment.** Cost data will be attached to every actor and event in every possible scenario,

computing the cost of each scenario, were it to occur. A probability of occurrence for each possible scenario will be generated, providing for highly refined overall cost estimates (for operations, for maintenance, and perhaps earlier lifecycle phases) within a specified confidence interval.

With the above steps, this application will use MP with cost modeling to enhance tradespace analysis of UAV systems. The executable integrated architecture will provide for evaluation of UAV technologies and/or design alternatives across a range of operational scenarios utilizing MBSE tools and notations.

Current commercial MBSE tools support creation of a very small number of operational scenario instances compared to what is possible. The validity of these tradespace analyses, however, stands to be substantially improved by expanding the number of scenario variants considered, to include a wider range of possible nominal and off nominal behaviors in both the system under design and the environment. In particular, resulting cost estimates (e.g., for UAV software development, as well as UAV missions during operations & maintenance) are impacted by underrepresentation of possible scenarios and the lack of probability data on those scenarios. One of our objectives is to increase the resolution of source data used for cost model computations. We will compare, contrast, and possibly integrate methods in Phase 5 for cost modeling in MP and SysML depending on the Phase 4 results.

The technical approach involves cycling AFIT-developed operational scenarios through the MP modeling process, whereby alternate events are captured for each actor in each scenario. This will produce a superset of scenario variants from the behavior models, suitable for input to tradespace analysis models and cost model hooks developed in SysML.

With this we can capture lifecycle cost attributes for each function point in the architecture, based on internal and external interactions in the MP models. We can also capture cost attributes for each actor and each event in each generated scenario for use in mission cost effectiveness analyses. Phase 6 will develop further improvements to MP. Based on Phase 4 results these may include an improved event trace generator and a user-friendly GUI.

### **Task 3. Next-Generation, Full-Coverage Cost Estimation Model Ensembles**

NPS will continue extending the scope and tradespace interoperability of cost models and tools in Phase 6. This is based on stakeholder feedback in earlier phases for parametric model enhancements and tool automation improvements.

Leveraging Phase 5 cost driver research, Phase 6 will develop prototype systems engineering and software cost models and tools for piloting and refinement, and extend the estimation capabilities toward full-coverage in conjunction with USC.



The cost modeling activities will engage domain experts for Delphi estimates, evolve baseline detailed definitions of the cost driver parameters and rating scales for use in data collection, and gather initial data and determine areas needing further research to account for wide differences between estimated and actual costs. Phase 6 will continue the extension in scope of the models and tools and their piloting and refinement.

For tool interoperability we will integrate cost models in different ways with MBSE architectural modeling approaches and as web services (also part of Task 2 piloting). We will also automate systems and software risk advisors that operate in conjunction with the cost models.

We will expand on earlier phase results for cost modeling web services. We previously developed a working prototype web service for Orthogonal Defect Classification Constructive Quality Model (ODC COQUALMO) supporting tool interoperability (costing in the cloud). COQUALMO was demonstrated in Phase 1 with only a subset of cost factors. Per interested stakeholders we will develop full implementations of selected parametric cost models in Phase 6.

NPS will provide domain expertise to USC and Georgia Tech for the SysML cost model integration effort. We will add the COCOMO software cost model formulas, and risk assessment capabilities for Expert COSYSMO Error! Reference source not found. and Expert COCOMO Error! Reference source not found... In Phase 5, and we'll continue those and evaluate Monte-Carlo approaches within SysML.

This task is also tied to Task 2 piloting with MBSE cost model interfaces. In Phase 6 we will assess MP for automatically providing cost information from the architectural models. This is analogous to the SysML method for extracting attributes and they will be compared. MP will be used to extract software sizing information. It will generate function point measures which will be input into COCOMO. We will also assess how MP architectural elements can be mapped into systems engineering cost model inputs.

## **APPENDIX A: LIST OF PUBLICATIONS RESULTED**

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### 1-Books

B. Boehm, J. Lane, S. Koolmanojwong, R. Turner, "The incremental Commitment Spiral Model," Chinese language version.

### 2 -Papers in peer-reviewed journals

Accepted to INCOSE Systems Engineering Journal Special Issue of best papers from CSER 2016: B.Boehm, C.Chen, L.Shi, K.Srisopha, "Maintainability Readiness Levels for Software-Intensive Systems," Date TBD, 2017.

## 2 - Papers in conferences with full paper review

R. Alfayez, C. Chen, P.Behnamgader, K. Srisopha, B. Boehm, "An Empirical Study of Technical Debt in Open-Source Software Systems, Proceedings, CSER 2017.

B. Boehm, "Improving and Balancing Software Qualities," Technical Briefing, ICSE 2016. B.Boehm, C.Chen, L.Shi, K.Srisopha, "Maintainability Readiness Levels for Software-Intensive Systems," CSER 2016, March 2016.

B.Boehm, C.Chen, L.Shi, K.Srisopha, "The Key Roles of Maintainability in an Ontology for System Qualities," INCOSE International Symposium, July 2016.

Celia Chen, Reem Alfayez, Kamonphop Srisopha, Barry Boehm and Lin Shi, "Why is it Important to Measure Maintainability, and what are the Best Ways to Do it?," accepted poster paper, ICSE 2017.

B. Boehm, "Software Cost Estimation Meets Software Diversity," accepted as Technical Briefing, ICSE 2017.

Chen, C., Alfayez, R., Srisopha, K., Shi, L., and Boehm, B. "Evaluating Human-Assessed Software Maintainability Metrics." In Proceedings, NASAC 2016.

Shi, L., Chen, C., Wang, Q., & Boehm, B. "Is It a New Feature or Simply "Don't know yet"? On Automated Redundant OSS Feature Requests Identification." In Proceedings, ACM RE Next 2016.

Wu, B., Shi, L., Chen, C., Wang, Q., & Boehm, B. "Maintenance Effort Estimation for Open Source Software: A Systematic Mapping Study." In Proceedings, ICSME 2016.

Boehm, B., Chen, C., Srisopha, K., & Shi, L. 2016. "The Key Roles of Maintainability in an Ontology for System Qualities." In Proceedings, INCOSE IS 2016.

Hira, Anandi, Shreya Sharma, and Barry Boehm. "Calibrating COCOMO® II for projects with high personnel turnover." Proceedings of the International Conference on Software and Systems Process. ACM, 2016.

Hira, Anandi, and Barry Boehm. "Function Point Analysis for Software Maintenance." Proceedings of the 10th ACM/IEEE International Symposium on Empirical Software Engineering and Measurement. ACM, 2016.

Hira, Anandi, and Barry Boehm. "Using Software Non-Functional Assessment Process to Complement Function Points for Software Maintenance." Proceedings of the 10th ACM/IEEE International Symposium on Empirical Software Engineering and Measurement. ACM, 2016.

Hira, Anandi, and Barry Boehm. "Combatting Use Case Points' Limitations with COCOMO® and Relative Difficulty." Proceedings of the 23rd Asia-Pacific Software Engineering Conference. IEEE, 2016.

Ross, Adam and Rhodes, Donna, "Interactive Model Trading for Resilient Systems Decisions," Proceedings, CSER 2017.